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AN EXPERIMENTAL CONTRIBUTION TO THE QUESTION OF THE DEPTH OF THE ZONE OF FLOW IN THE EARTH'S CRUST

FRANK D. ADAMS
McGill University, Montreal

INTRODUCTION

In connection with an experimental study of the Flow of Rocks, on which the author has been for some time engaged and in which he has been assisted by grants from the Carnegie Institute of Washington, the question of the depth of the Zone of Flow beneath the surface of the earth has naturally presented itself. This subject has an interest and importance, not only as bearing upon many problems in geology, but also on one question at least of direct importance in mining, namely, that of the depth to which mineral-bearing fissures may extend in the earth's crust.

That the outer portion of the earth's crust was susceptible of subdivision into a Zone of Fracture and a Zone of Flow was set forth by Professor Heim in his great work *Untersuchungen über den Mechanismus der Gebirgsbildung*, and was based upon the data which he had obtained from his life-long studies in the Alps.[1] In this epoch-making work Heim states that as the result of his observations in the Alps he concludes that the upper surface of the Zone of Flow for very resistant rocks, such as granites, is 2,200 to 2,600 meters or about a mile and a half below the surface of the earth, and considerably nearer the surface for limestone and other softer rocks. After thirty years of additional study Heim, in a recent paper, records his opinion that these depths are too small, that the Zone of Flow lies deeper within the earth's crust, but as to how much deeper he does not venture an opinion.[1]

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[1] Albert Heim, *Untersuchungen über den Mechanismus der Gebirgsbildung*, Basel, 1878, Bd. II, 92.

President Van Hise in the interpretation of the results of his classic work on the ancient crystalline rocks of the United States in the district of the Great Lakes, reached a similar conclusion with reference to the twofold subdivision of the earth's crust, but placed the upper surface of the Zone of Flow at a considerably greater depth than Heim, namely, 12,000 meters or 7.4 miles.

Van Hise based his estimate on a mathematical calculation having as its starting-point the crushing weight of a cube of granite at the surface of the earth as determined by a testing machine in the ordinary manner adopted in testing the strength of building materials—granite being one of the strongest and at the same time one of the commonest rocks in the earth's crust. This calculation was made for Van Hise by Professor Hoskins who, taking the figures for the crushing strength of granite thus obtained, endeavored to calculate the depth below the earth's surface at which the pressure would be so great that all empty cavities would close as a result of plastic flow, even in the case of the hardest rocks like granite. This depth he fixed at four miles, or 6,520 meters. This is indicated by line "*a*" in Fig. 1. If however the cavities were filled with water Hoskins calculated that they would remain open to a depth of 6.4 miles, or 10,350 meters. This depth is shown by the line "*b*" in Fig. 1.

Van Hise then assumed an additional factor of safety, and took 12,000 meters as a depth at which not only all cavities would close but the hardest and most resistant rocks would flow—this being therefore the upper surface of the Zone of Flow in the earth's crust. This depth has been indicated by the line "*c*" in Fig. 1.

In order to make such a calculation, even in the very simple case treated by Hoskins, certain assumptions must be made and the result obtained varies widely with these assumptions. Consequently, the figures obtained by Hoskins have not behind them the weight of a mathematical certainty. They are founded on

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[1] Albert Heim, *Geologische Nachlese*, No. 19 (*Vierteljahrschrift der Naturfor. Gesel. in Zürich*, 1908, 45).

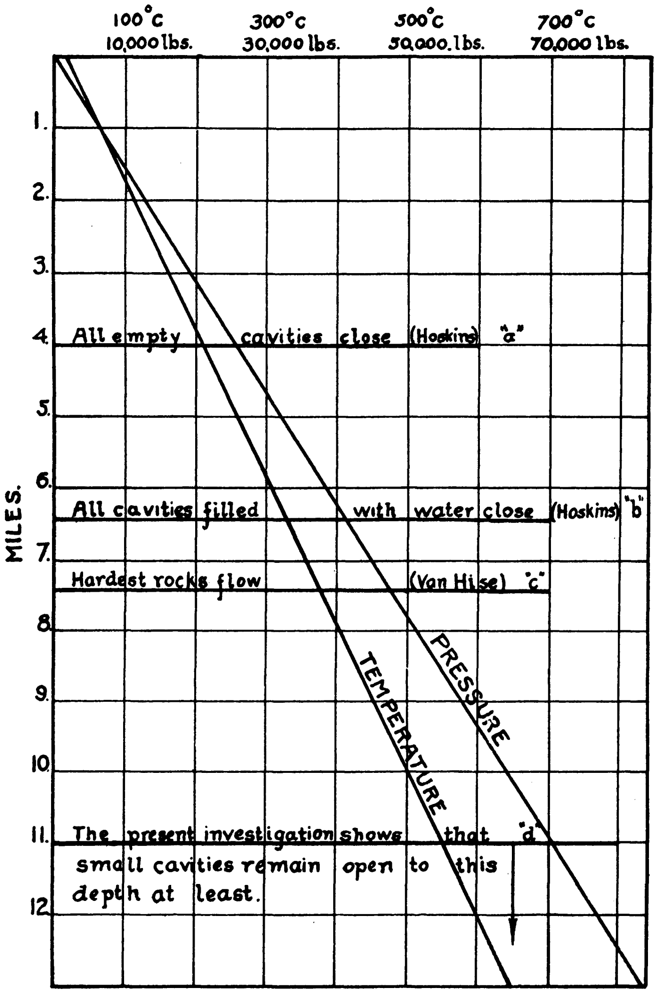

FIG. 1.—Showing the Pressures and Temperatures which are believed to exist within the Earth's Crust at successive depths to a distance of thirteen miles from the the surface. The temperatures are expressed in degrees Centigrade and the pressures in pounds per square inch. (see pp. 98 and 110).

certain assumptions and have a probability no greater than the assumptions on which they are based.

The mathematical aspect of this question, however, as well as that of certain other questions arising out of the experimental results set forth in the present paper are treated at length by Mr. L. V. King, of the Department of Physics of McGill University, in the accompanying paper. As will be seen, Mr. King is of the opinion that the assumptions made by Mr. Hoskins are not permissible.

But even if the calculation were not based on these doubtful mathematical assumptions, a whole series of additional assumptions are made which very seriously affect the final result, as Van Hise himself points out. These are: (*a*) that rocks below the surface of the earth have the same strength as at the surface; (*b*) that the rocks constituting the earth's crust are all of the same kind; (*c*) that the temperature within the earth's crust is the same as that at the surface; (*d*) that the presence of water does not affect the character of the deformation; (*e*) that rocks yield as readily by fracture as by flow; (*f*) that rocks break as readily by fracture, when the deformation is slow as when it is rapid; (*g*) that the rocks whose crushing strength is taken as a datum are among the strongest in the earth's crust.

Van Hise believes that these assumptions are such that could we apply corrections for each of the factors concerned, we should find that these—with the exception of the first—"would tend to lower the figures given, that is to say, to bring the Zone of Flow nearer to the earth's surface." "But I suspect," he goes on to say, "that the various factors giving too great a depth are of far greater consequence than the one factor giving too small a depth."[1] He suspects the depth given by Hoskins is much too great, "probably twice too great."

The circumstance, however, that all these disturbing factors exist and that no account is taken of them in the calculation in question is frequently altogether forgotten and, consequently, positive statements are often made based upon this calculation, such as the following from a well-known book which has recently appeared.

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[1] *A Treatise on Metamorphism*, 189.

> We find that at a depth of about six miles beneath the surface the pressure must become so great that all rocks known to us would be crushed by it. If it were attempted, for example, to tunnel in rock at this depth, the roof of the tunnel would immediately collapse and the opening be entirely sealed up. The microscopic pores in the rock would likewise and for the same reason be closed.

As a matter of fact the figures for the depth of the Zone of Flow, which are under discussion, hang upon a slender thread of doubtful mathematical analysis enfolded by a cloak of many conjectures.

In his Presidential Address before Section G of the British Association for the Advancement of Science in 1904, Hon. Chas. A. Parsons discusses among other questions the possibility of sinking a shaft into the earth's crust to a depth of 12 miles, and in a letter which appeared in *Nature* (October 20, 1904) Geoffrey Martin expressed the opinion that at this depth the pressure would be so great that the walls of such a shaft, if it were constructed, would close in, owing to the viscous flow of the rock through which it passed. Parsons, in a note commenting on this letter, shows that a misplaced decimal point made the figures given by Professor Martin too high, and states that at the depth mentioned the pressure of the wall rock would amount to 44 tons per square inch, which in his opinion would be insufficient to close the shaft, adding:

> I think that the evidence at present available leads to the conclusion that after a small amount of shrinkage of the shaft sides inward had taken place, a state of equilibrium would be established, enabling the surrounding rock in its state of great compression to withstand the so-called hydraulic pressure down to a depth from the surface of at least 12 miles.

He concludes,

> It would however be interesting to subject a cylinder of granite or quartz rock carefully fitted into a steel mould and having a small hole bored through its center to a pressure of say 100 tons to the square inch and see what shrinkage in the hole would result.

As it seemed that important information might be obtained along the line suggested by Parsons, an experimental study of the question was undertaken, from which some rather interesting results have been obtained.

To go back for a moment to the important work of President Van Hise, it will be noted that in looking over the factors enumerated by him as not having been taken into consideration, three are manifestly of much greater importance than the others in their bearing upon the depth of the Zone of Flow. These are: (1) the influence of pressure upon the rigidity of rocks in the deeper parts of the earth's crust; (2) the existence and influence of the higher temperature found at such depths; (3) the effect of long continued pressure as compared with pressure applied for short periods.

The other factors referred to are apparently of less importance. Thus the softer rocks—sandstone, limestone, etc.—occurring in the earth's crust do not extend to any considerable depth; the existence of water in the deeper parts of the earth's crust is a matter about which there is still a considerable amount of doubt; while it would seem that the strength of granite may be taken as fairly representative of that of the stronger rocks of the relatively superficial portion of the crust.

The question then arises as to whether it is possible, in approaching the question of the depth of the Zone of Flow from an experimental standpoint, to reproduce the conditions of rigidity, temperature and long continuance of pressure which exist in the earth's crust and thus give due value to these three hitherto doubtful factors in the problem. It would seem that this can be done approximately at least in the case of the first and second of these factors, but that it is practically impossible to accurately reproduce the third experimentally, for it is impossible in an experimental research to extend the duration of an experiment over decades or centuries. But even here some approach can be made to the reproduction experimentally of the conditions of this third factor, in the first place by extending the duration as much as possible, and secondly by the substitution of a relatively higher pressure during the shorter period within which the experiment is necessarily confined for the lower pressure existing in nature for longer periods, since a higher pressure during a shorter time will approximate at least in its results to the effects produced by a lower pressure for a longer time.

Before the attempt is made to reproduce the conditions of pressure and temperature which obtain within the earth's crust, it is necessary to form as clear a conception as possible as to what these conditions really are. And here we are confronted with difficulties at the outset—for neither the pressure nor the heat existing as successive depths within the earth's crust can be calculated or otherwise determined accurately.

In order, however, to obtain some approximate measure of the pressure which exists at successive depths below the surface of the earth—and it is only the outermost portion of the crust extending to a depth of say 50 miles that comes into consideration for the present purpose—two assumptions, among others, will be made: (*a*) that the rocks composing the earth's crust are incompressible, and (*b*) that they are free from tangential stresses set up by the contraction of the earth's interior through secular cooling or by other causes. As a matter of fact, however, the rocks composing the crust are compressible and they are probably in most parts of the earth's crust in a state either of compressive or tensile stress. The first factor of compressibility, however, probably does not introduce any very serious error if omitted from consideration, but the second factor of tangential stress is more important and probably varies greatly not only at different points at or near the surface but at different depths below the surface. The data in our possession are inadequate to enable its influence to be calculated, but the investigations of Chamberlin, Woodward, Hoskins, and others[1] go to show that above the "Level of No Strain" great arches, if formed in the relatively cold surface crust, would be incompetent to sustain more than a small fraction of their weight and would thus collapse, tending to equalize the stresses in each successive zone.

For the purpose of this inquiry, the pressure at successive depths below the surface of the earth is assumed to be the weight of a column of rock equal in height to the depth in question. The specific gravity of the rock is taken as 2.8. These pressures are shown in Fig. 1.

It is also impossible to arrive at an accurate knowledge of the temperature within the earth's crust at successive depths below the surface. As is well known, the temperature gradient within the earth's crust shows considerable variations.

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[1] See Chamberlin and Salisbury, *Geology*, I, 553 ff.

A careful study of these variations has recently been made by Königsberger and Mühlberg. According to these authors:

> It may be assumed that all over the earth in flat countries where the subsoil consists neither of comparatively recent eruptive rocks nor of deposits liable to change, there prevails a normal geothermic gradient. All deviations from the normal gradient are due to local influences: uneven surface of soil (mountains, valleys), the presence of great reservoirs of water (lakes, the sea), and heat producing processes in the interior of the earth or incompletely cooled eruptive masses.[1]

The average of the gradient of 32 borings in flat country in rocks which are neither of eruptive origin nor subject to considerable chemical alteration is given by Königsberger and Mühlberg as 1° Centigrade in 32.9 meters.

The geothermic gradient adopted as shown in Fig. 1 is based on this value.

The view that this temperature gradient continues uniformly downward in the earth's crust has been controverted by Strutt, who from investigations into the radio-activity of the rocks of the earth's crust concludes that the temperature rises uniformly to 1500°C., and then remains constant at that temperature to the center of the globe. This conclusion, however, does not affect the consideration of the present question, seeing that this temperature would not be attained until a depth had been reached which is much greater than those whose temperatures are made the subject of study in the present paper.

THE EXPERIMENTAL METHOD EMPLOYED

Two rocks were employed in this investigation and two series of experiments were carried out with each.

In the first series with each rock, the attempt was made to reproduce the conditions of pressure to which rocks are subjected at various depths within the earth's crust, both as to intensity and, as far as possible, as to duration; while in the second series of experiments the third element of temperature was also introduced.

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[1] J. Königsberger and Mühlberg, "On Measurements of the Increase of Temperature in Bore Holes, etc." *Trans. Inst. of Mining Engineers*, London, 1910, XXXIX, Pt. IV, 9.

In every experiment a column of the rock, very accurately ground to the dimensions of .5 inch in diameter and 1.57 inch long, was taken and through it two holes were drilled. These holes were, as nearly as possible, .05 inch in diameter. One of these passed through the vertical axis of the column from top to bottom. The other passed transversely through the middle of the column, being at right angles to the other hole but a little to one side of it, so that the two holes did not actually intersect. A wire was then drawn to fit the hole exactly, so that the slightest change in the diameter of the hole could be detected by passing the wire into it.

A round bar of nickel steel, 3¼ inches long and 2½ inches in diameter, was then taken and a hole very slightly smaller in diameter than the rock column was accurately drilled through it in the direction of the longitudinal axis. This bar was then heated slightly, and thus expanded just sufficiently to allow the column of rock to be slipped in so as to occupy a position in the middle of this bar or thick-walled tube. The tube was then allowed to cool. The perforated rock column enclosed in its steel tube is shown in Fig. 2. The rock was thus held firmly on all sides by the steel, but the size of the hole was such that the shrinking of the tube upon the column did not compress the rock more than was required to effect a perfect mechanical fit, and in this way to give the requisite lateral support to the rock when the latter was submitted to compression in a vertical direction. Preliminary experiments showed that this operation did not in the slightest degree affect the size of the holes which had been bored through the column, and also showed that if the latter were unsupported below, a load of 7,250 lbs. on its upper end would shove it down through the tube.

If the experiment was to be conducted at ordinary temperatures, a disk of paper was then placed on either end of the column to equalize the pressure and two pistons of hardened "Novo" steel, ground so as to pass easily into the ends of the tube were inserted, by means of which pressure could be brought to bear upon the enclosed column. The whole was then placed in a powerful press and the enclosed rock submitted to a pressure equivalent to any required depth beneath the surface of the earth for a period varying from a few hours to two and a half months. Upon the conclusion of the experiment, the apparatus was removed from the press; the pistons, which could be readily withdrawn, as well as the disks of paper if any had been employed, were removed. The question as to whether the vertical or longitudinal hole had undergone any constriction was determined by ascertaining whether the wire would still pass through the hole which it had been drawn to fit, the slightest change in size being readily detected. The steel tube with its enclosed rock column was then placed in a lathe and the steel surrounding the middle portion of the column was turned off until only a film remained. This, where it covered the

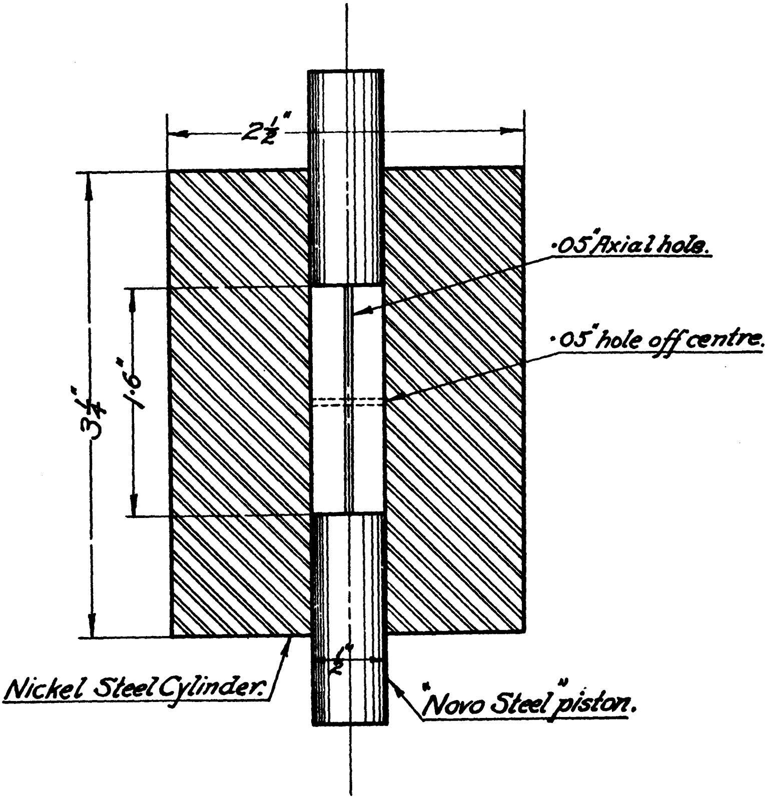


FIG. 2.—Showing the Column of Rock with a vertical and a transverse hole drilled through it, enclosed in a heavy tube of nickel steel.

ends of the transverse hole, was then removed, and the question as to whether there had been a constriction of the transverse hole was determined by attempting to pass the wire through it.

In those experiments in which the element of heat was introduced, the tube with the enclosed column was placed before compression in a suitably constructed apparatus in which it could be maintained at a constant temperature, during the experiment, the temperature being measured by a properly calibrated thermoelectric couple.

For the purpose of experimental investigation, it was important to select rocks which not only represent the chief types composing the earth's crust but which also possess physical characteristics which render them suitable for experimental purposes, that is to say, rocks which are massive, rather fine in grain, uniform in character, and free from cracks and other flaws.

Two rocks which fulfil these conditions excellently are:—(1) the Lithographic Limestone from Solenhofen, Bavaria; (2) the Red Granite from Westerly, Rhode Island.

LITHOGRAPHIC LIMESTONE, SOLENHOFEN, BAVARIA

This may be taken as representing the softer sedimentary type of rocks which are found more abundantly at or near the surface in the upper portions of the earth's crust. The Solenhofen limestone is very fine in grain, very massive in character, and of a buff color. It breaks with a splintery or choncoidal fracture, and Heim speaks of it as one of the most brittle of rocks. A chemical analysis showed that the variety employed in these experiments consisted of carbonate of lime holding 3.52 per cent of impurities. It has a specific gravity of 2.603 when dry and is slightly porous, as shown by the fact that when allowed to remain under water in vacuo for 24 hours it absorbs 1.63 per cent of water.

In order to ascertain the crushing strength of the rock as determined in the manner usually employed in the case of building stones, etc., a series of six 2-inch cubes were very carefully sawn out of a block of the limestone, and having been accurately ground, were tested in compression, observing all the precautions required to attain the most accurate results. These determinations were carried out in the Testing Laboratories at McGill University, a 100-ton Wicksteed machine being employed, and gave the following results:

40,600 lbs. per square inch
28,400 " " " "
29,635 " " " "
33,788 " " " "
32,725 " " " "
32,750 " " " "
Average = 32,980

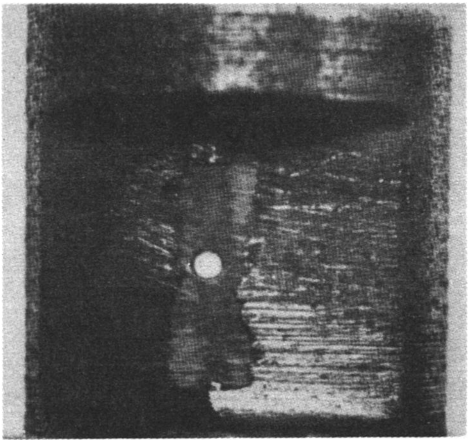
The average crushing strength of the Solenhofen limestone is, therefore, 32,980 lbs. per square inch. It is thus seen to be an extremely strong rock; stronger, in fact, than an ordinary granite under compression.

Four experiments were first made with columns of Solenhofen limestone, the pressure being increased in each successive experiment so as to represent successively greater and greater depths within the earth's crust, the element of time being also varied. These experiments were all, however, conducted at the ordinary temperature. The results are shown in Table I on p. 109.

It will be seen from these experiments, that at the ordinary temperature no trace of movement could be detected in the rock at a pressure equivalent to a depth of 15 miles below the earth's surface, even after the pressure had been continuously applied for two and a half months. When, however, the pressure was increased to that which is supposed to exist within the earth's crust at a depth of 20 miles below the surface, the experiment being continued for two and a half months, a certain movement was observed. At a pressure representing a depth of 30 miles and to a still more marked extent at a pressure equivalent to a depth of 40 miles, movements had taken place in 7 hours which resulted in the partial filling of the holes passing through the column. As will be noted, a depth of 31 miles represents a pressure of 100 tons to the square inch.

It is thus seen that Solenhofen limestone at the ordinary temperature and under conditions of cubic compression—which are the conditions of pressure to which it is subjected in the earth's

PLATE I



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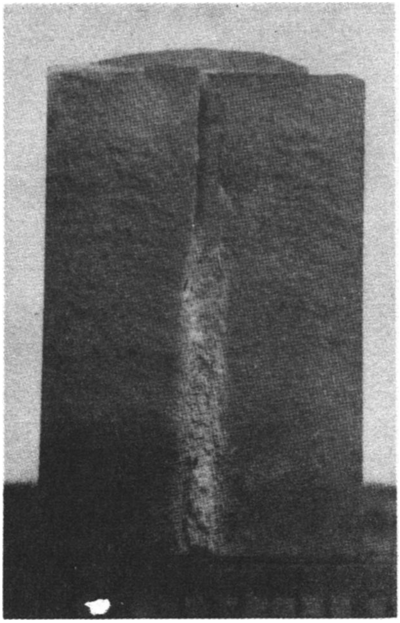

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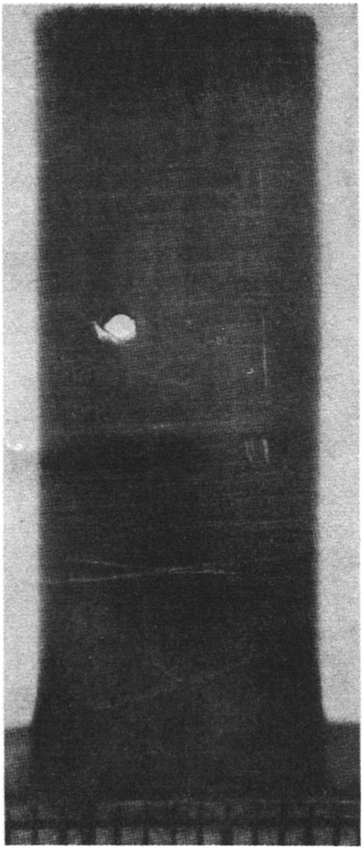

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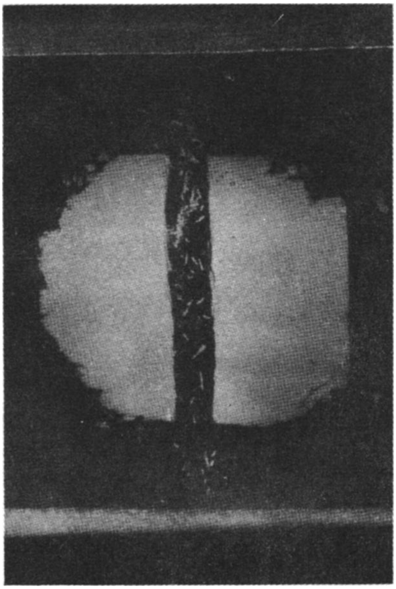

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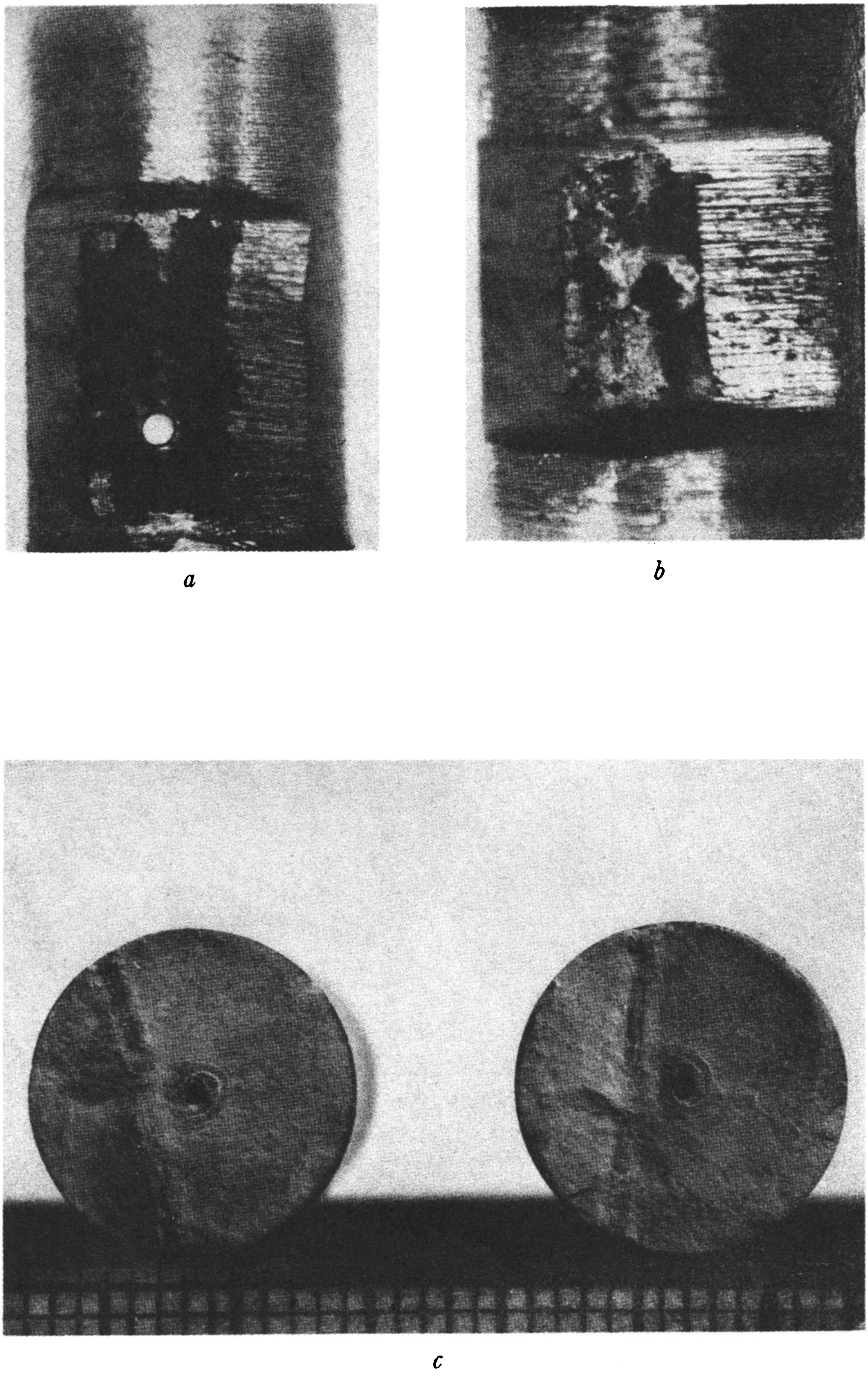
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crust—will retain its form and will not flow into holes traversing it even when submitted for months to a pressure three times as great as would suffice to crush it instantly under the ordinary conditions obtaining at the surface of the earth.

TABLE I

Showing the Effects Produced when Columns of Solenhofen Limestone—at the Ordinary Temperature—Are Submitted to Pressures Existing at Successive Depths within the Earth's Crust

No. of Experiment	Pressure Pounds per Square Inch	Kilos. per Sq. Cent.	Depth below Surface of the Earth Represented by the Pressure	Duration of the Pressure	Results
359......	96,000	6,750	15 miles	2½ mos.	No movement of any kind. (See Plate I, Fig. *a*)
360......	128,000	9,000	20 miles	2½ mos.	Transverse hole smaller. Vertical hole partly filled. (See Plate I, Fig. *d*)
382......	193,000	13,570	30 miles	7 hrs.	Transverse hole unaltered. Vertical hole partly filled.
520......	200,000	14,060	31 miles	½ hr.	Transverse hole flattened. Vertical hole mostly filled. (See Plate I, Fig. *b*)
383......	257,000	18,070	40 miles	7 hrs.	Transverse hole flattened. Vertical hole mostly filled. (See Plate I, Fig. *c*)

The movement noted in the cases of experiments 520 and 383—representing depths of 31 and 40 miles—seems to be of the nature of flow, so far as it affects the transverse holes, these holes becoming flattened. But as shown in the descriptions of Plates I and II, the movement takes place by the development of minute fractures along the course of the vertical holes, small fragments of the rock becoming detached from the walls. The author desires to express his thanks to Dr. J. A. Bancroft of McGill University, to whom he is indebted for the photographs from which these prints were taken.

A second series of experiments was then made with a view to ascertaining the effect produced by the introduction of the factor of heat.

According to the investigations of Debray,[1] the highest temperature to which calcite can be submitted in open vessels without decomposition is 450°C. This is the temperature which is supposed to exist at a depth of nine miles below the surface of the earth.

Perforated columns of the limestone, identical in size and shape with those employed in the first series of experiments, were enclosed in heavy tubes of steel as before. The tubes having been heated to a temperature somewhat higher than 450°C., the column was inserted and the tube then allowed to cool and contract about it. The steel pistons were inserted in the usual manner and the whole being placed in a specially constructed heating apparatus, the rock was maintained at a temperature of 450°C. while submitted to the required pressure.

An investigation into the relative expansion of the nickel steel and the Westerly granite carried out by N. E. Wheeler, B. Sc. of the Department of Physics of McGill University, shows that with a gradually rising temperature the granite at first expands more slowly than the steel and then more rapidly.[2] The expansion curves intersect, i.e., both materials expand equally at a temperture of 400°C., and with the temperature of 450°C., at which all the experiments with two exceptions were conducted, the difference in expansion of the two materials is extremely small, the expansion of the granite being slightly greater, which serves only to cause the enclosing tube to hold the granite column a little more firmly.

As it was impossible with the apparatus employed to maintain an absolutely constant temperature without the continuous attention of the experimenter, these experiments at high temperatures could not be extended over periods of several months as in the case of the experiments conducted at ordinary temperatures. The shorter time during which the experiment lasted, however, was in a manner compensated for by increasing the pressure, a higher pressure for a relatively shorter time producing in the case of plastic deformation the same effect as a relatively lower pressure for a longer period. While therefore the temperature, except in the last experiment, was maintained at 450°C., equivalent to a depth of 9 miles below the surface, the pressure was increased until it was equivalent to a depth of 15 miles below the surface, while the time varied from 70 seconds to 70 hours. The results obtained are set forth in the following table.

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[1] C.R., 1867, 603.

[2] "On the Thermal Expansion of Rock at High Temperatures," *Trans. Roy. Soc. of Canada*, 1910.

TABLE II

TABLE SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF SOLENHOFEN LIMESTONE—HEATED TO 450°C.—ARE SUBMITTED TO PRESSURES EXISTING AT DEPTHS OF 10 AND 15 MILES WITHIN THE EARTH'S CRUST

No. of Experiment	Heat	Pressure Lbs. per Sq. Inch	Kilos. per Sq. Cent.	Depth Equivalent to Pressure Employed	Time	Results
480......	450°C.	64,000	4,500	10 miles	7 hrs.	Holes remain unchanged. No movement of any kind.
374......	450°C.	96,000	6,750	15 miles	70 secs.	Holes become slightly contracted.
362......	450°C.	96,000	6,750	15 miles	7 hrs.	Holes become slightly contracted.
367......	450°C.	96,000	6,750	15 miles	25 hrs.	Holes become slightly contracted.
370......	450°C.	96,000	6,750	15 miles	70 hrs.	Holes become slightly contracted.
371......	450°C.	96,000	6,750	15 miles	70 hrs.	Holes become slightly contracted.
365......	490°C. to 513°C.	96,000	6,750	15 miles	70 hrs.	Transverse hole closed completely.

In this series of experiments it is to be noted that when the rock is submitted to the maximum temperature which can be employed without decomposing it, namely 450°C., which is equivalent to a depth of nine miles below the surface of the earth, no effect is produced if the pressure be raised to that which obtains at a depth of 10 miles. If, however, the pressure is still further increased till it reaches that to which the rock would be exposed at a depth of 15 miles, a slight diminution in the diameter of the holes is observed, even if this pressure is only maintained for a period of 70 seconds. This movement, however, is not increased even if the rock be maintained at this pressure and temperature for an additional period of 70 hours. In the last experiment, however, when the heat rose for a time to 513°C. the transverse hole, as noted, became completely closed, which may have been connected with a partial disassociation of the Ca CO_3 molecule caused by the high temperature.

GRANITE, WESTERLY, RHODE ISLAND, U.S.A.

A knowledge of the behavior of this rock under deep seated conditions is of especial importance, because it is a typical representative of the great class of plutonic igneous rocks which make up so large a portion of the earth's crust.

This well-known rock is a fresh, fine-grained, massive, pale pink granite, composed essentially of biotite, microcline, orthoclase, and quartz. A detailed description of its microscopic characters as well as the results of a study of its elastic constants are give in Publication No. 46 of the Carnegie Institute of Washington.[1]

The crushing strength of the granite was determined on 2-inch sawed cubes, all the precautions referred to in the case of the Solenhofen limestone being employed to secure accuracy. The results were as follows:

1st cube = 28,340 lbs. per square inch
2d cube = 26,410 " " " "
Average = 27,375 " " " "

It will thus be observed that the rock is not quite so strong as the Solenhofen limestone under the ordinary conditions of a test for crushing strength.

Columns of the granite were prepared, bored, and placed in their enclosing tubes of steel in the manner already described. As in the case of the Solenhofen limestone, a series of experiments were first made at the ordinary temperatures. The following table shows the results obtained:

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[1] Adams and Coker, *An Investigation into the Elastic Constants of Rocks*, etc., Carnegie Institute of Washington, Washington, 1906.

TABLE III

SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF WESTERLY GRANITE—AT THE ORDINARY TEMPERATURE—ARE SUBMITTED TO PRESSURES EXISTING AT SUCCESSIVE DEPTHS WITHIN THE EARTH'S CRUST

No. of Experiment	Pressure Lbs. per Sq. Inch	Kilos. per Sq. Cent.	Depth Represented by the Pressure	Duration of Pressure	Results
361......	128,000	9,000	20 miles	2½ mos.	Holes unaltered—No movement.
373......	160,000	11,250	25 miles	2½ mos.	Holes unaltered—(See Plate II, Fig. a).
356......	199,000	13,990	30.86 miles	15 hrs.	Holes unaltered—No movement—
357......	200,000 (100 tons to sq. inch)	14,060	31 miles	2½ mos.	Transverse hole unaltered. Vertical hole partly closed at one end by rock powder.
358......	222,500	15,640	35 miles	2½ mos.	Transverse hole completely filled. Vertical hole largely filled with rock powder—(See Plate II, Fig. b).

It is thus seen that granite at the ordinary temperature, but under the conditions of cubic compression which obtain in the earth, will sustain a load of about 100 tons to the square inch, that is to say, a load rather more than seven times as great as the crushing load of the granite at the surface of the earth under the conditions of the ordinary laboratory test.

In this connection an observation made by P. W. Bridgman is of interest, namely, that under an external hydrostatic pressure amounting to 24,000 atmospheres, or 360,000 pounds to the square inch, continued for 3 hours the cavity of a sealed glass tube did not close or show any sensible change in size or form.[1]

Reference has been made to the nature of the movement observed in the case of the Solenhofen limestone, which seemed to be due in part to flow and in part to fracture.

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[1] Quoted by R. A. Daly in his paper on the "Nature of Volcanic Action," *Pro. Am. Acad. of Arts and Sciences*, June, 1911, p. 53.

In the case of the granite the holes when filled are closed by what appear to be minute fragments of granite detached from the walls. In the case of experiment 358, after the removal of the steel the vertical hole as seen from either end was still open and was unaltered in size or shape for a distance of .08 and .24 inch respectively. Beyond that, however, it was blocked up. On removing the steel so as to expose the extremities of the transverse hole, it was found that one end of this hole was completely filled up, no trace of the opening remaining. The locus of the hole was occupied by what seemed to be a part of the rock, finer in grain than the rest and which looks as if it were a perfectly compacted mass of powdered granite. The other extremity of the hole had also been completely closed, although an outline marking its original position could be seen—it was filled with finely granular material clearly crushed granite, imbedded in which were a few relatively larger fragments giving to the whole the appearance of a breccia.

In order to eliminate any error which might be conceived to have been introduced by the pistons expanding under the load and pressing against the sides of the steel tube, thus reducing the amount of pressure exerted on the rock and also to give the rock a better chance to deform by the application of the pressure to the center of the end faces instead of over the entire surface of the faces in question, another experiment was arranged in which the column and its enclosing tube were identical in all respects with those already described but the pistons were .4 inch in diameter while the column had the usual diameter of .5 inch. The proper load to give a pressure of 160,000 lbs. per square inch, equivalent to a depth of 25 miles below the surface, was then applied by this smaller piston to the center of the end faces of the column, for a period of two and a half months, but no change whatever was produced in either the transverse or the vertical hole.

A second series of experiments was then carried out with the Westerly granite in which the factor of heat was introduced.

For the same reason as mentioned in the case of the Solenhofen limestone, the duration of the experiment was necessarily shorter than in the case of the experiments conducted at the ordinary temperature. The results of the experiments are as follows:

TABLE IV

SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF WESTERLY GRANITE—HEATED TO 450°C. AND 550°C.—ARE SUBMITTED TO THE PRESSURE EXISTING AT A DEPTH OF 15 MILES WITHIN THE EARTH'S CRUST

No. of Experiment	Heat	Pressure Lbs. per Sq. Inch	Kilos. per Sq. Cent.	Depth Equivalent to Pressure Employed	Time	Results
375......	450°C.	96,000	6,750	15 miles	70 secs.	Holes unaltered. No movement.
376......	450°C.	96,000	6,750	15 miles	70 hrs.	Holes unaltered. No movement.
381......	550°C.	96,000	6,750	15 miles	70 hrs.	Holes unaltered. No movement.

As before mentioned, the temperature of 450°C. is that which exists at a depth of 9 miles below the surface, while a temperature of 550°C. is that which is found 11 miles below the surface.

Experiment 381 is one the results of which are of especial interest, for it shows that under the conditions of temperature which exist at a depth of 11 miles below the surface of the earth, open cavities in granite—at least those of relatively small dimensions—*will not close even if the factor of time is allowed for by increasing the pressure over and above that which occurs at a depth of 11 miles by nearly 50 per cent.*

It is further to be noted that this depth of eleven miles (see Fig. 1) is not the extreme depth at which experiment shows that open cavities may exist. They may be present at still greater depths, but the fact that the steel by which the lateral resistance was secured experimentally commences to soften at temperatures of a little over 550°C. makes it impossible to push the experimental investigation by the method employed, to the study of the deportment of the rock at higher temperatures, that is to say, at greater depths.

THE DEPTH TO WHICH MINERAL VEINS AND ALLIED DEPOSITS MAY EXTEND

The present investigation seems to have a rather important bearing on a question of great economic importance, namely, the depth to which mineral veins and replacement deposits may extend in the earth's crust. It must first be noted that the question of the size of a cavity is one which must be considered in this connection. In the accompanying paper Mr. King has investigated this subject mathematically and shows that in the case of any given rock a pressure might be reached which would be sufficient to crush in larger cavities, but the collapse of the walls instead of leading to the complete closing of the cavity in question would merely result in the formation of a number of smaller spaces, which would remain open permanently or which could only be closed by a greatly increased pressure.

This factor has been eliminated in the present investigation by having the holes in the case of all the experiments identical in size and relatively small.

It is the depth to which these smaller cavities and passages will remain open that is the really important one in connection with the question of the depth to which mineral deposits may extend. For although a great fissure vein may have been developed by the filling of a great fissure, it is considered by some authorities that the crystallographic force of the growing minerals filling the vein has had an important influence in opening up a comparatively narrow fissure, thus making a relatively wide vein in what was originally a comparatively narrow crack. But whether this be so or not, a class of deposits which are much more numerous and more important than "true fissure veins," namely replacements, do not require any originally wide fissures for their development, but are formed by the passage of mineralizing solutions or vapors through narrow cracks or fissures, which serve merely to give such solutions or vapors under high pressures a passage into and through the rock, which they attack and alter and in which they deposit their burden of ores and other valuable minerals by a process of replacement. All, therefore, that is needed for the formation of such deposits are very narrow cavities or fissures to give the mineral bearing solutions access to the rock in which the ores are to be concentrated. Many deposits in shear zones and shattered strips of rock are of this character, as well as other replacement deposits in which the lines of the original fissures are now entirely obliterated.

Whatever, therefore, may be the fate of great yawning chasms if these are formed within the earth's crust at the depths under consideration in this paper, it is clear that if these are crushed in, smaller cavities will survive even in the crushed mass of rock formed by the collapse of the walls of such a cavity, and will afford ample passage for solutions, vapors, etc., and, therefore, provide the conditions required for the deposition of mineral deposits of the replacement type at least at the great depths in question.

SUMMARY OF CONCLUSIONS

1. The calculations which have been made as to the depth below the earth's surface at which all cavities in the earth's crust would be closed by plastic flow, based on the crushing strength of rocks at the surface of the earth, are erroneous.

2. At ordinary temperatures but under the conditions of hydrostatic pressure or cubic compression which exist within the earth's crust, granite will sustain a load of nearly 100 tons to the square inch, that is to say, a load rather more than seven times as great as that which will crush it at the surface of the earth under the conditions of the usual laboratory test.

3. Under the conditions of pressure and temperature which are believed to obtain within the earth's crust, empty cavities may exist in granite to a depth of at least 11 miles. These may extend to still greater depths, and if filled with water, gas or vapor, will certainly do so, owing to the pressure exerted by such fluids or gases upon the inner surfaces of such cavities or fissures.

4. Since the existence of open spaces through which aqueous solutions, vapors, or gases can traverse a rock is a factor in the development of mineral veins and replacement deposits, such veins and deposits may be formed within the earth's crust to a depth of at least 11 miles below the surface. That is to say, they may extend to a much greater depth than it is possible to follow them by any method of mining now employed.

DESCRIPTION OF PLATES

PLATE I

FIG. *a*.—Shows a column of Solenhofen limestone (Exp. 359) which has been submitted to a pressure equivalent to a depth of 15 miles within the earth's crust for 2½ months. The steel tube has been partially removed so as to expose the transverse hole. This latter is seen to have been unaffected by the pressure.

Fig. *b*.—This is a column of Solenhofen limestone (Exp. 520) which has been submitted to a pressure of 100 tons to the square inch equivalent to a depth of 31 miles below the surface of the earth, for half an hour. The steel which enclosed it has been completely removed. There has been a slight movement of the nature of plastic flow developed in the rock, owing to which the transverse hole originally circular in outline has been flattened so that it now presents a lenticular cross-section.

Fig. *c*.—This is experiment 383. The column of Solenhofen limestone was submitted to a pressure equivalent to a depth of 40 miles below the earth's surface—for seven hours. The steel tube was then removed but in the process the column broke in two along the line of the transverse hole (seen at the top of the photograph) and also split vertically along the line of the vertical hole. A vertical section of one-half of the column is shown. For about one-half its length along the central part of the column the vertical hole remains unaltered but from this unaltered part, and with increasing intensity toward either end of the column minute crescentic cracks form on the wall of the hole, along which cracks little fragments of the rock separate and fill the hole more or less completely.

Fig. *d*.—This is a reproduction of a photograph of a thin section cut vertically through the column of Solenhofen limestone of experiment 360. It shows the walls of the vertical hole with the minute cracks referred to in Fig. *c*.

Plate II

Fig. *a*.—Shows a column of Westerly granite (Exp. 373) which has been submitted to a pressure equivalent to a depth of 25 miles below the surface of the earth for 2½ months. The steel tube has been partially removed exposing the transverse hole, which has been absolutely unaffected by the pressure.

Fig. *b*.—Shows a column of Westerly granite (Exp. 358) which has been exposed to a pressure equivalent to a depth of 35 miles below the surface of the earth, for 2½ months. Under this pressure, as seen, the transverse hole has been filled in. The irregular dark spot, marking the original position of the hole, is caused by the breaking away of a little granite when the steel tube was being removed.

Fig. *c*.—This shows the cracks referred to in the description of Plate I, Figs. *c* and *d;* but they are especially pronounced because in this case (Exp. 384) the steel tube was thinned away about the middle of the column of Solenhofen limestone, permitting the latter to bulge out laterally, thus giving a greater freedom of movement. It was submitted to a pressure of 204,000 lbs. per square inch, equivalent to a depth of rather over 31 miles below the surface of the earth.